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NOISE EMISSION FROM OPEN TURBULENT PREMIXED FLAME

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Abstract

Combustion noise is one of the main problems encountered in most of practical combustion systems. An experimental investigation has been carried out to study flame noise and the effect of mainstream air velocity and the equivalence ratio on it. Tests were carried out using an open turbulent premixed flame stabilized behind a conical bluff body (with 60° included angle and 0.42 blockage ratio). The fuel used was natural gas. Flame noise was measured by a condenser microphone coupled with audio frequency spectrometer, labcard, FFT analyzer and PC computer. Data analyses were carried out using a special software. The results showed that the flame noise spectrum, for any upstream velocity, is dependent on the equivalence ratio, and this dependence is as clear in rich limit as the lean one. It was found also that the sound pressure level is dependent not only on the equivalence ratio but also on the upstream mixture velocity.

Keywords: flame noise.

Introduction

Combustion instabilities occur in many practical systems such as power plants, jet engine after-burners and rocket engines. Unstable combustion has many undesirable features. It induces large amplitude oscillations of the flow and mechanical vibrations of the combustor and of the other components of the system, it enhances the heat transfer rates at the combustor walls and in extreme cases it leads to the total loss of the system [1]. It is common knowledge that flow systems become noisier when they become turbulent and when the combustion is started in them. A steadily burning laminar flame makes practically no noise, whereas explosions, even of quite small bubbles of gas mixtures produce a strong sound or shock waves. Flames also become noisy when they are turbulent; in which noise is associated with pressure pulses due to irregularities in direction and speed of the flame front.

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To evaluate the flame frequency, the theory of the turbulent, as well as investigation of the stochastic phenomena will be necessary. Thus it is possible to establish the relationship between the turbulent pulsation and flame frequency. The turbulent pulsation and flame frequency are not identical, but are in close connection with each other. The turbulent pulsation expresses the variation of the instantaneous value of the velocity, while the flame frequency expresses the fluctuation of radiation, pressure or other characteristics of the flame front developed as a result of the turbulent pulsation. These temperature and pressure oscillation phenomena developed as a resultant of the physical, chemical and ambient effects [2].

The simplest source of sound is known as a *monopole* and may be visualised as a pulsating balloon. The turbulent flame may be considered as a collection of burning elements of the combustible gas (turbulent balls) formed mainly at the interface between fuel and air and acoustically is equivalent to a collection of monopole sound sources. Since the pulses from the monopole sources tend to interfere with each other, the total noise intensity will fluctuate in a random manner [3]. In other words, from considerations of the mechanism of combustion in a turbulent flow, it is postulated that such a flame may be represented as a random distribution of burning elements of the combustible mixture, each of which is evolving an increased volume of heated gases. The resultant displacement of the surrounding gases gives rise to a superposition of pressure waves that are radiated away from the boundaries of the flame. Thus, it is suggested that any turbulent flame may be represented by an acoustic model consisting of a distribution of monopole sources of radiation of varying strengths and frequencies throughout the zone of combustion [4, 7].

Two different sources of combustion noise may be distinguished. The first one is the monopole source noise; the pressure wave radiated by individual droplets of liquid fuel or isolated element of gaseous fuel as they ignite and expand. The second possible source is the extra turbulence produced by the flame, which is superimposed on the background of the original turbulence that would be present in the same flow system without combustion.

The principal reasons for investigating combustion oscillations are to determine their range of existence so that they can be avoided and to find ways to suppress them. Regular combustion oscillation produces a number of undesirable side effects as well as the sound. These are mostly mechanical and are associated with increasing rate of heat transfer during oscillation, and fatigue due to oscillating stresses. In cases where the fuel/air ratio varies due to the oscillation a reduction in operating efficiency may occur. On the other hand, the combustion efficiency may well increase in those cases where the oscillation is driven by improved mixing [5].

Table 1
Summary of the Literature Review

Reference	Experimental data	Measuring technique	Results
THOMAS and Williams (1966) [8]	Experimental arrangement for preparing and igniting bubbles of combustible gas C_2H_4, N_2 and O_2	Condenser microphone, Schlieren system and rotating drum camera	– A monopole flame source can be regarded as any other simple acoustic source whose strength is determined as the rate of volume variation. – The pressure in the sound wave depends on the rate of change of the generation rate by the source. – The sound emitted depends markedly on flame speed and the geometry of combustion. – Thermoacoustic efficiency lies in the range 10^{-8} to 10^{-6}.
ARNOLD (1972) [10]	Premixed and diffusion flames $\Phi = 1.2$, ethane-air, gasoline, kerosene	Schlieren photography	There is a possibility to reduce the noise output of large combustion systems (jet engine, for example) by more effective control of the flame configuration and stability.
GIAMMAR and PUTNAM (1972) [12]	Premixed flames $d = 1.25$, 1.5 and 2 in singly and pairs at fuel rich side natural gas-air	Condenser microphone	– Thermoacoustic efficiency varying with the square of the Mach number. – The turbulence level rather than the velocity itself was the significant factor. – The noise output varies with the square of the firing rate.
SMITHSON and FOSTER (1965) [13]	Meker burner $\dot{V} = 5.5$, 6.2 and 7.1 l./min. town's gas	Condenser microphone	– The measured thermoacoustic efficiency (η) is maximum at blowoff. – A further phenomenon of sound emission due to combustion instability was found at the rich limit of flammability.

Table 1
continued

GIAMMAR and PUTNAM (1970) [15]	Two impinging fuel jets $d = 0.04$ and 0.0635 in. Octopus burner (8 impinging fuel jets) diffusion flames natural gas	Condenser microphone	– The thermoacoustic efficiency is of order of 10^{-8} to 10^{-6}; (this range is compatible with that reported in the literature for turbulent premixed flames) [11]. – Buoyancy controlled flames show that a noise output varies with the square of the firing rate. – Flames in the thrust controlled region tend to show a linear increase in sound pressure output with firing rate. – The noise output increased rapidly with increase in jet spacing.
OHIWA et al. (1973) [20]	3 diffusion flames, two-dimensional open burner (30×64.5 mm) flame stabilized by pilot flame (propane-air $\Phi = 0.85$) $u = 2, 8, 10$ m/s $Tu = 0.5, 0.6, 2, 6.6,$ and 7.5% gaseous propane	Condenser microphone, electrostatic probe, fine bare thermocouple optical system and photomultiplier	– Noise generation is associated with the eddy flames. – An increase in the velocity may be found to elevate the sound pressure level (SPL). – Because of similar flow conditions, the noise spectra of the three flames are very nearly the same. – In order to reduce the combustion noise level of the industrial burner systems, it is necessary to establish flames which are free of any coherent structure, in addition to preventing resonance oscillations due to the combustor geometry.
PRICE et al. (1969) [21]	Open premixed flame $d = 17$ mm, flame stabilization by H_2 pilot flame, ethylene-air diffusion flame, $d = 1$ mm, H_2-methane	Condenser microphone	– The pressure in the sound waves generated by a turbulent premixed flame depends quantitatively on the rate of change of the rate of combustion of the fuel-air mixture in the flame. – The same result was obtained for turbulent diffusion flame, if it is assumed that the fuel and air burn in stoichiometric proportions. – Mean emission intensities of C_2 radicals depend linearly on the volume flow rate of combustible mixture.

Table 1
(continued)

SHIVASHANKARA et al. (1975) [23]	Open premixed turbulent flame, $d = 0.96$ in., $u = 100 - 600\,\mathrm{ft/s}$, $\Phi = 0.8 - 1.25$, H_2 pilot flame for stability, propane and ethylene	Condenser microphone, light emission detector	- Flames were loudest around the luminous zones or the sources of combustion noise are primarily located in the luminous flame brush. - The noise generation mechanism can be attributed to the time derivatives of the chemical reaction rate.
KOTAKE and TAKAMOTO (1987) [24]	Premixed flame, $d = 8 - 18\,\mathrm{mm}$, (circular and rectangular nozzles), $\Phi = 0.8 - 3$, city gas pilot flame for stability, $u = 10 - 30\,\mathrm{m/s}$ propane-air	Condenser microphone, HWA	- For fuel lean flames, the acoustic power is proportional to flow velocity $u^{2.8\sim3.2}$, and for circular nozzle, further it is proportional to $d^{1.9\sim2.1}$. The proportionality constant depends on the equivalence ratio, the nozzle shape and size. - For fuel rich flames, it is proportional to $u^{3.3\sim3.7}$, and to the nozzle area. The proportionality constant depends on the equivalence ratio.

The sound emitted from combustion systems is classified into the *combustion roar* generated by the inhomogeneous structure of the turbulent flame, and the *resonant sound* produced by the resonance or feedback phenomena of the system [9].

The practical importance of the combustion noise has given rise to a large number of the theoretical and experimental studies. Much of our understanding of combustion noise and the mechanism of sound emission from isothermal jets and flames is due to the theoretical and experimental studies of BRAGG (1963) [5], LIGHTHILL (1962) [14], SMITH and KILHAM (1963) [4], HASSAN (1974) [28] and STRAHLE (1971) [11]. *Table 1* presents the summary of the literature review.

During these studies most of the factors affecting combustion noise were investigated, but the knowledge of flame noise is still very far from perfection especially in case of bluff body stabilized flame. So the present study attempts to investigate the combustion noise emitted from a premixed flame stabilized behind the bluff bodies, especially near the flammability limits.

Test Rig

A schematic diagram of the test facility used in the present work is shown in *Fig. 1.* Its construction and the importance of each part were explained at [18, 19]. Air is supplied by two blowers, which are separated in a different place outside the laboratory to isolate its sound, through a long plastic pipe (about 20 m) to minimize the flow fluctuation and the pipes' vibration. For flame noise measurement a special set-up consists of condenser microphone, audio frequency spectrometer (type 2112), labcard, FFT analyzer and PC computer was added to the main test rig.

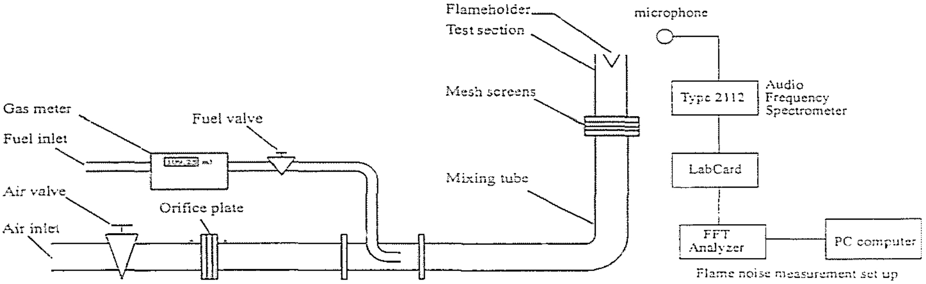

Fig. 1. Schematic diagram of the test rig

Test Procedure

For a certain mainstream air velocity, the fuel control valve was opened and the mixture was ignited with an electric torch until the flame was established behind the bluff body. After each ignition the spark plug was withdrawn to avoid the flame disturbances. Then, the fuel flow rate was gradually reduced until the lean limit of flammability (*Fig. 2*). Flame noise measurements using a condenser microphone were carried out for different equivalence ratios including the lean and the rich limits of flammability. SMITH and KILHAM [4]. BRIFFA et al. [6] and [17] concluded that at points very close to the flames, less than 30 burner diameter for a premixed flame, it was possible to determine the sound pressure levels and frequency spectra of the noise associated from the immediate vicinity of the flame brush, but no information was obtained relating to the direction of propagation of the sound. Conversely, in the farfield it was possible to determine the directionality and acoustic power of flame noise, but not the precise origin of the sound. So that the microphone was positioned at a distance of about 60 cm ($L/d = 20$) near the flame and at the flame root level, and connected with audio frequency spectrometer, labcard, FFT analyzer and PC computer. Data analyses were carried out using a special software. During the course of measurements we try to choose the times at which nobody works at the same laboratory or at the neighbouring laboratories, to avoid any noise coming from other sources.

Results and Discussion

Fig. 2 shows the flammable region and the flammability limits, among them some equivalence ratios (EQR) were chosen for the present flame noise measurements, while, *Fig. 3* shows a sample of flame oscillation time domain signal. At this figure and some other figures, the pressure amplitude is presented in Volt or mVolt and it must be mentioned here that there is a linear proportionality between the pressure amplitude in dB and the amplitude of the measured electrical signal in Volt. The effect of equivalence ratio on flame oscillation spectrum is shown in *Fig. 4*. The same result was found for different mainstream air velocity. It is clear from this figure that as the equivalence ratio increases the amplitude of flame oscillation increases all the same, and the lean limit of flammability is governed by the low frequency oscillation while the rich one is governed by some higher frequencies.

It was concluded by [3, 16] that the acoustic pressure should vary in the same manner as the rate of change of the free radical — generated in the reaction zone — emission intensity, but there is a lag in the pressure signal due to the time taken for the sound to reach the microphone. The change in the intensity of these free radicals in the reaction zone is proportional to the rate of change of its volume that affects the sound emission [9, 19 – 22]. Due to the two above conclusions, the results shown in *Fig. 4* explained probably at the same way, as the equivalence ratio increase the intensity of the different free radicals expected to be increased influencing the reaction zone volume and thermal expansion of it, causing an increase of the intensity of the emitted sound.

Figs. 5 – 8 show the normalized integral amplitude distribution of the flame noise time domain signals at different upstream flow velocity and at different equivalence ratio. From these figures one can notice that for a given velocity as the equivalence ratio increases the amplitude of flame oscillationincreases, and the same result is found for all the velocities tested.

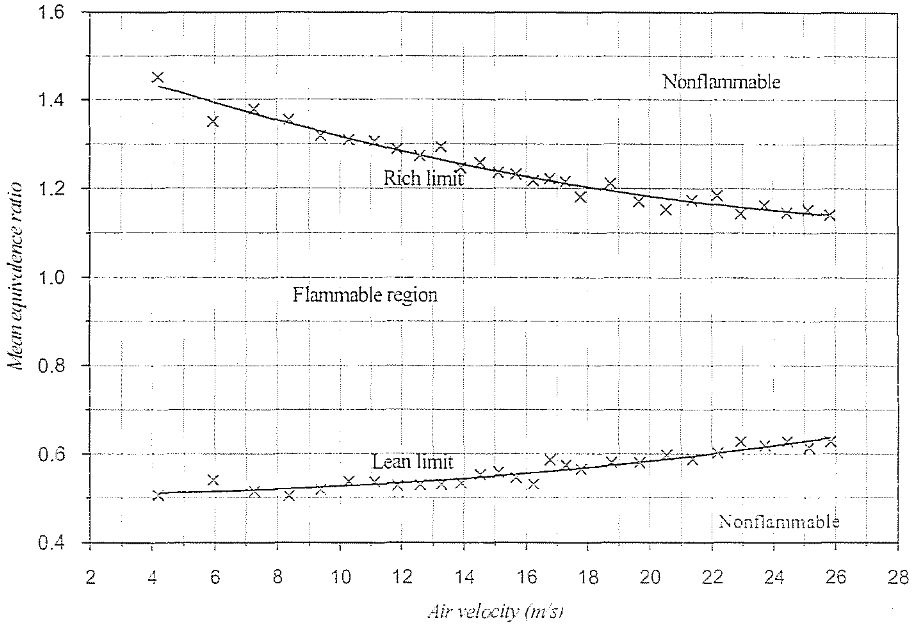

Fig. 2. Mean equivalence ratio versus the air velocity, (flameholder: cone, $BR = 0.42$, $h/d = 0$). [19]

Fig. 9 shows the normalized integral amplitude distribution for the flame noise time domain signals at the lean limit of flammability for the tested velocities. It is clear from this figure that as the velocity increases the weak extinction equivalence ratio increases [25] as well as the amplitude of flame oscillation [24]. The normalized integral amplitude distribution for the corresponding signals at the rich limit of flammability is shown in *Fig. 10*. It shows that as the velocity increases the rich extinction equivalence ratio decreases, while the amplitude of flame oscillation increases. The reasons behind these results are the change in flame configuration and structure and the change in flame speed due to the change of the upstream conditions [3, 10].

It was also postulated [3] that the sound intensity (I) is given by: $I = \overline{\Delta P^2}/\rho \cdot C$; where $\overline{\Delta P^2}$ is the mean square of the pressure fluctuation, ρ is the density of the medium and C is the velocity of the sound. The pressure fluctuations only occur when the rate of combustion changes and is given by: $\Delta P = (2\rho/D)\, E\,(E-1)\, r \cdot S_u^2$; where D is the distance from the microphone, E is the volumetric expansion ratio, r is the flame front radius and S_u is the burning velocity. It is clear from the above relation that the

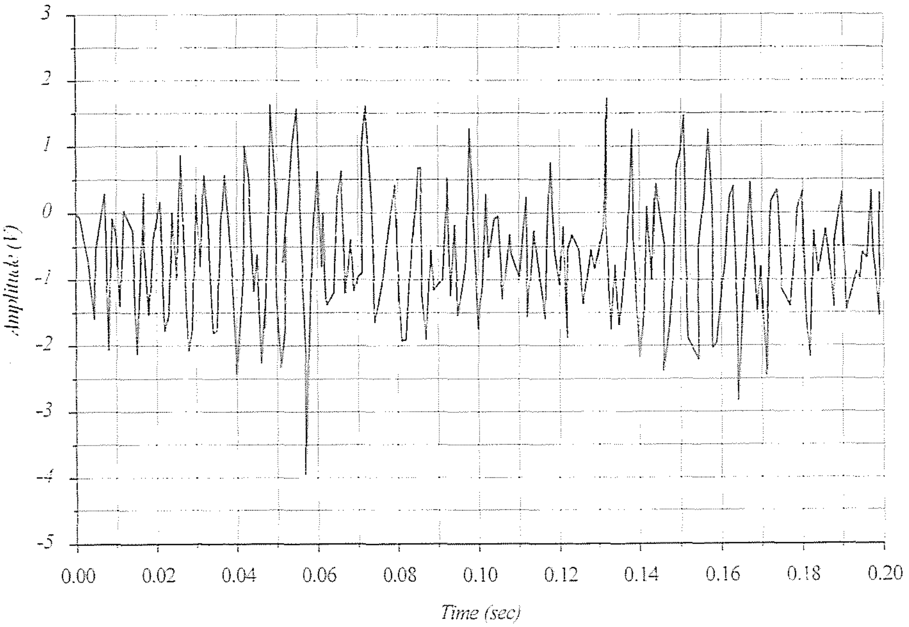

Fig. 3. Flame oscillation time domain signal, ($EQR = 1.3383$, flameholder: cone, $BR = 0.42$, $h/d = 0$, $u = 8.38\,\mathrm{m/s}$)

pressure fluctuation depends on the square of the burning velocity and by a simple combination between the above two relations, it will be clear that the noise intensity has a strong dependence on the burning velocity because it should vary as S_u^4.

It was concluded by SMITH and KILHAM [4] that the acoustic outputs were observed to change due to the variation in the flow velocity and in the air-fuel ratio, and they found also that there is a direct proportionality between the SPL and the product of upstream flow velocity (u), burner diameter (d) and the burning velocity S_u: $SPL\alpha\,(u \cdot d \cdot s_u)$. It was found that the thermoacoustic efficiency increases as the heat output increases [6], also the noise output was found to vary with the square of the firing rate [12], which means that the sound emission should increase as the equivalence ratio increases, and these probably also explain the results shown in *Figs. 5 – 10.*

Flame stabilization behind the bluff body occurs due to heat and mass transfer at the wake of the flameholder [25, 26]. Within this recirculation zone and in the shear layers — where the turbulent heat flux is large due to the large temperature fluctuation [27] — surrounding it, a lot of

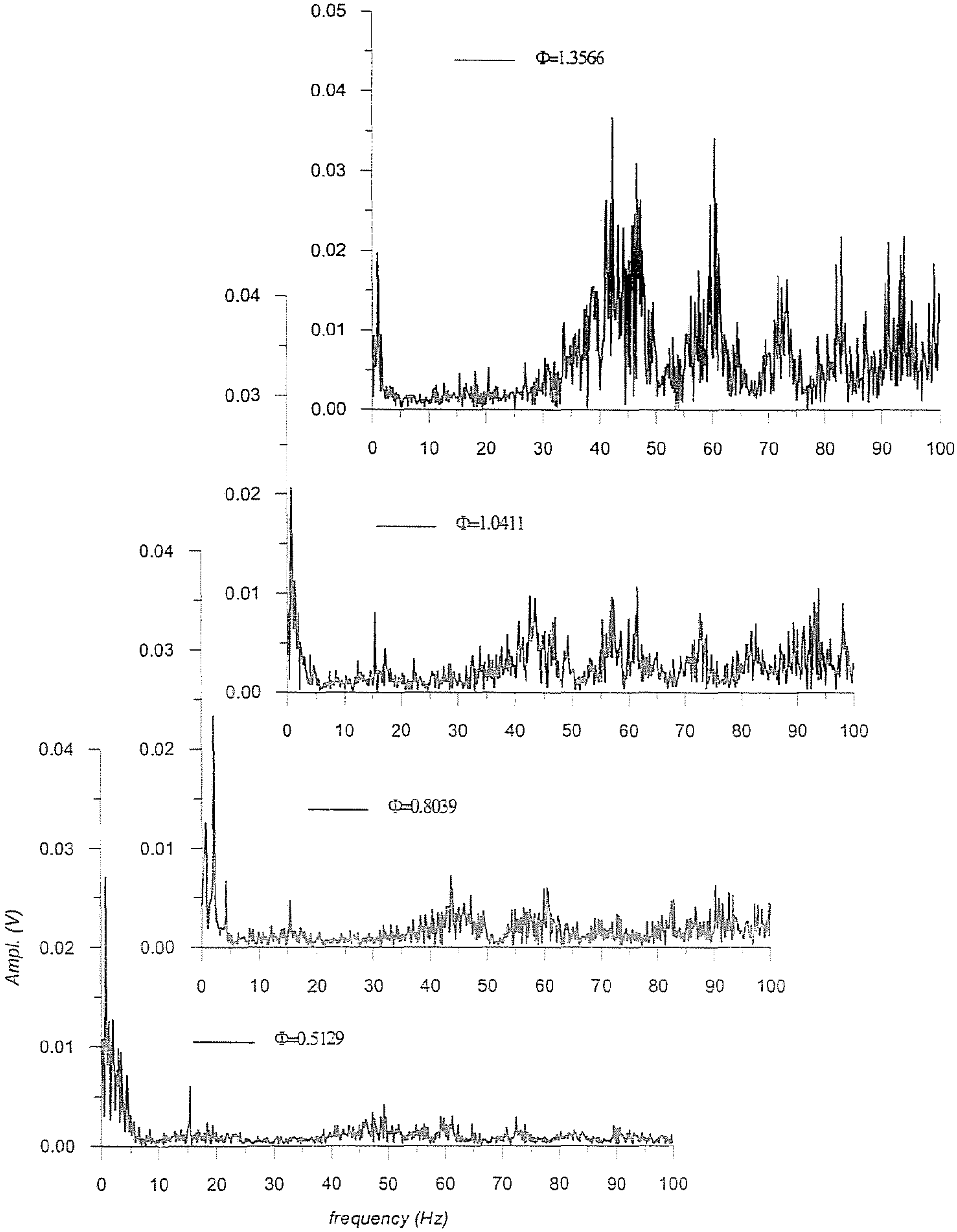

Fig. 4. The effect of equivalence ratio on flame oscillation spectrum, (flameholder: cone, $BR = 0.42$, $h/d = 0$, $u = 8.38\,\mathrm{m/s}$)

processes happen; there are small and big eddies recirculating through this region that is carrying mass, heat and momentum from one bucket to other ones. There is a combination of molecular, eddy and bulk effects producing turbulence and intense mixing [29, 30]. So as a result all of these processes is seen in the reaction zone the sound emission from the flame should be enhanced. There is also a possibility that fluctuating properties in the flame are produced or amplified by the inherent disturbances in the approaching flow [10].

Fig. 11 shows the inclination angle of the normalized integrated amplitude versus the equivalence ratio at different flow velocities. The same trend was found for all the tested flow velocities, but the values of angles are close to each other at the lean limit while the range is wide for the rich one. The big difference in the behaviour between the lean and rich limit of flammability, as it was mentioned before, is due to the variation of the pressure fluctuation, and consequently the noise output, with the square of the firing rate [13].

Fig. 12 shows the relation between the sound pressure level and the equivalence ratio at different flow velocities. It is clear from this Figure that for all flow velocities as the equivalence ratio increases the sound pressure level increases, too, and it also increases as the flow velocity does, the same trend was found by [4, 6, 15, 16]. SMITH and KILHAM [4] mentioned that the sound pressure is proportional directly to the flow rate and suggested that, as the flow rate increases, the strength of the elementary sources in the flame should increase by the same proportion, resulting in a similar increase in the acoustic energy output. They also concluded, as we mentioned before, that $SPL\alpha\,(u \cdot d \cdot s_u)$.

Conclusions

From analysis and discussion of the results, it may be concluded that the flame noise spectrum, for any upstream velocity, is dependent on equivalence ratio. This dependence, as shown in *Figs. 9 – 11*, is clearer at the rich limit of flammability than the lean one. It was concluded also that the lean limit of flammability is governed by the low frequency oscillation while the rich one is governed by some higher frequencies [32]. It was found that the sound pressure level is dependent not only on the equivalence ratio but also on the upstream mixture velocity and there are clear proportionalities between the SPL, the equivalence ratio, and the flow velocity. It was concluded also that some detailed studies for flame turbulence structure, free radical emission and recirculation zones mixing process must be carried out to understand more the present phenomenon [3].

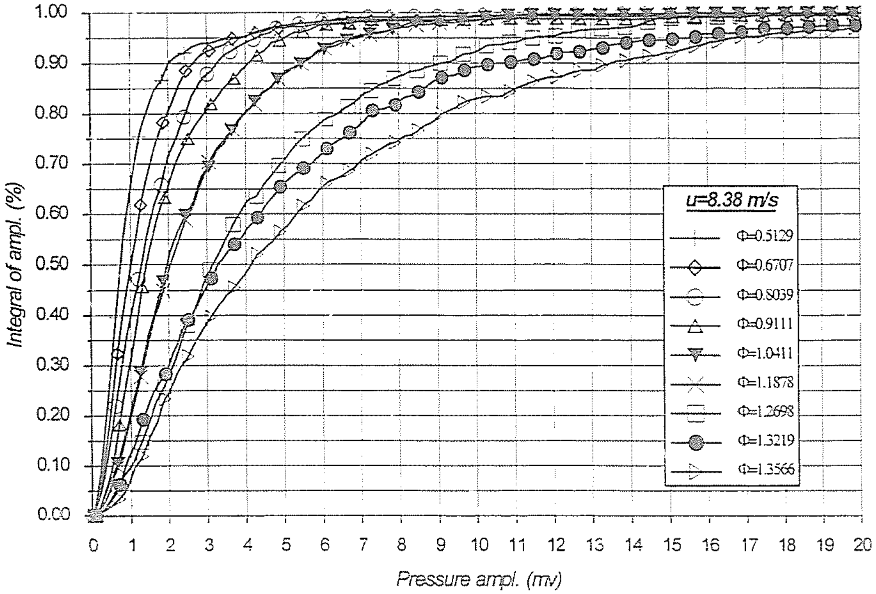

Fig. 5. Normalized integral of amplitude distribution for different EQR, (flameholder: cone, $BR = 0.42$, $h/d = 0$, $u = 8.38\,\text{m/s}$)

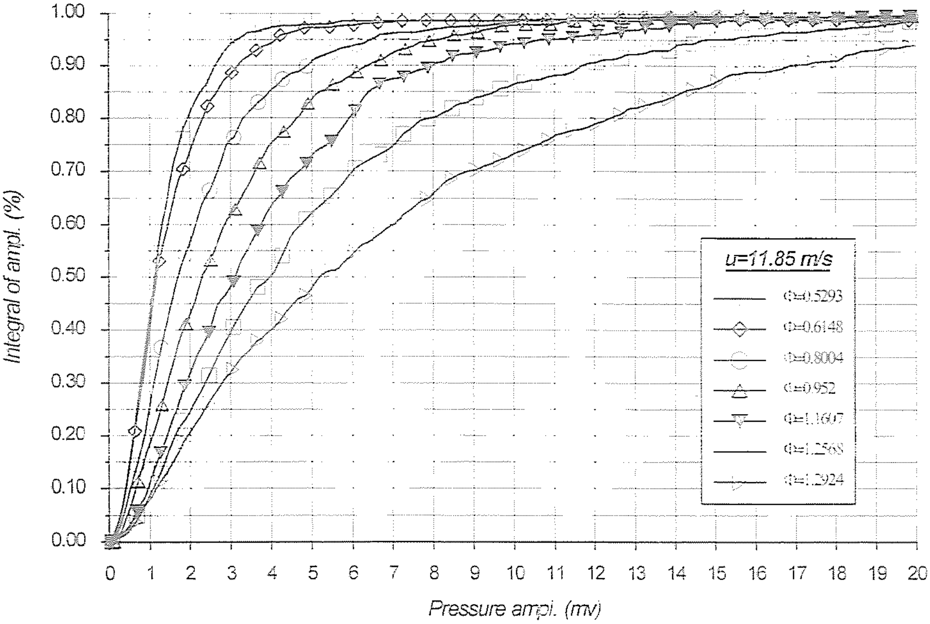

Fig. 6. Normalized integral of amplitude distribution for different EQR. (flameholder: cone. $BR = 0.42$, $h/d = 0$. $u = 11.85\,\text{m/s}$)

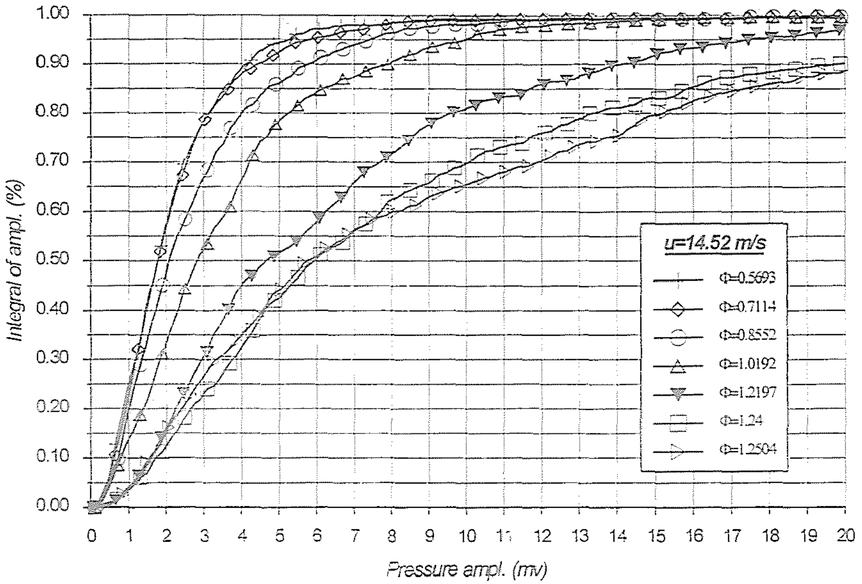

Fig. 7. Normalized integral of amplitude distribution for different EQR, (flameholder: cone, $BR = 0.42, h/d = 0$, $u = 14.52\,\mathrm{m/s}$)

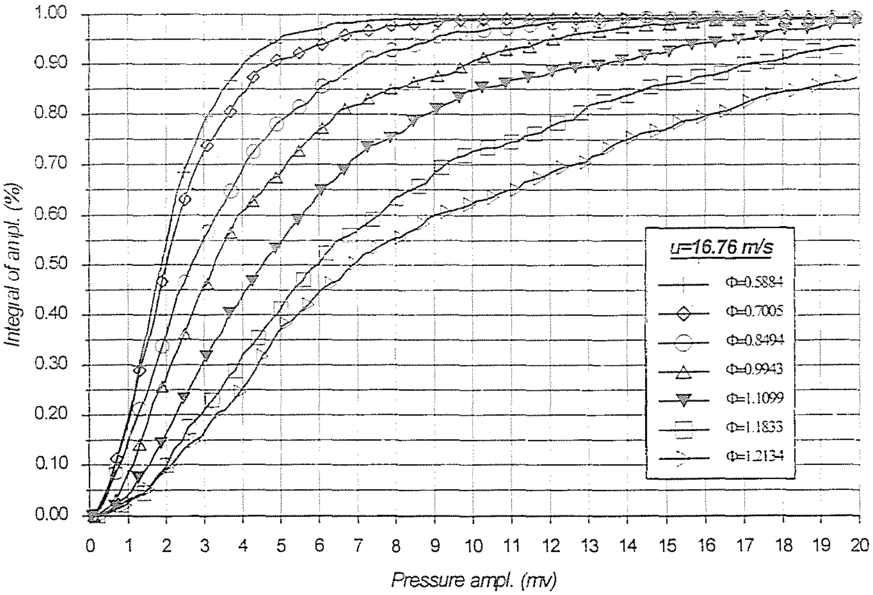

Fig. 8. Normalized integral of amplitude distribution for different EQR, (flameholder: cone, $BR = 0.42$, $h/d = 0$, $u = 16.76\,\mathrm{m/s}$)

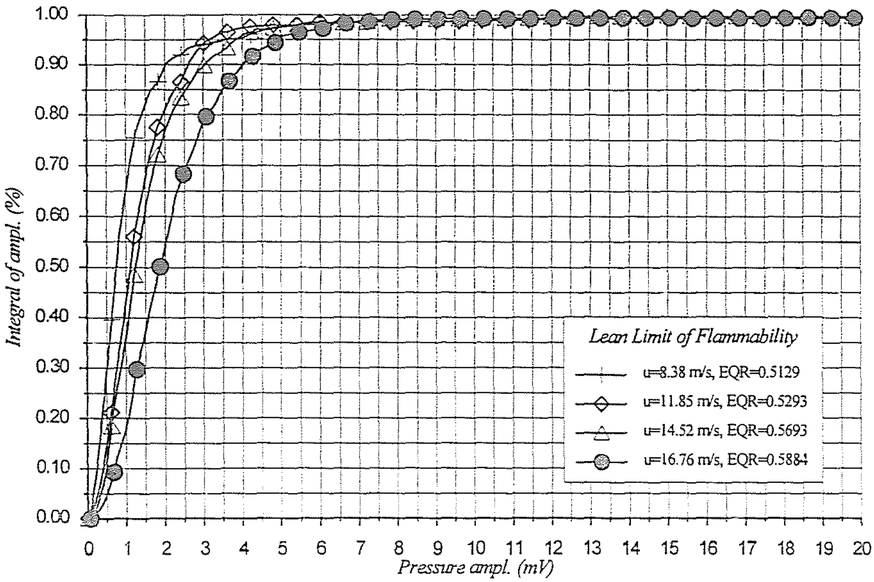

Fig. 9. Normalized integral of amplitude distribution at lean limit of flammability at different flow velocity

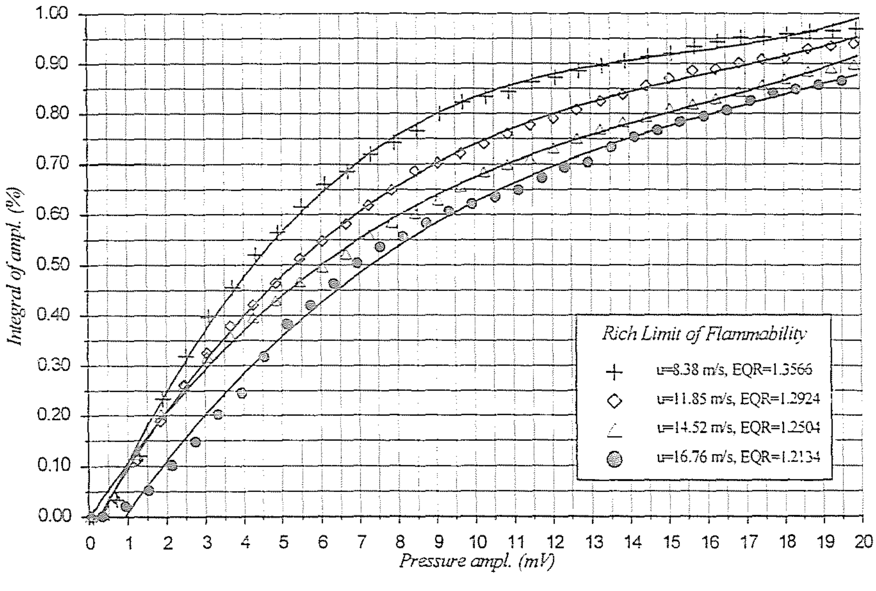

Fig. 10. Normalized integral of amplitude distribution at rich limit of flammability at different flow velocity

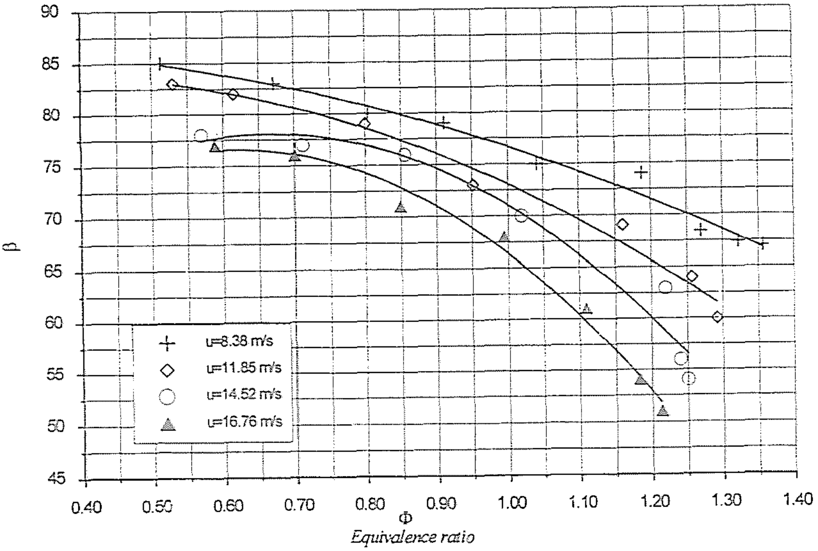

Fig. 11. The inclination angle of the normalized integrated amplitude versus the equivalence ratio at different flow velocity, (flameholder: cone, $BR = 0.42$, $h/d = 0$)

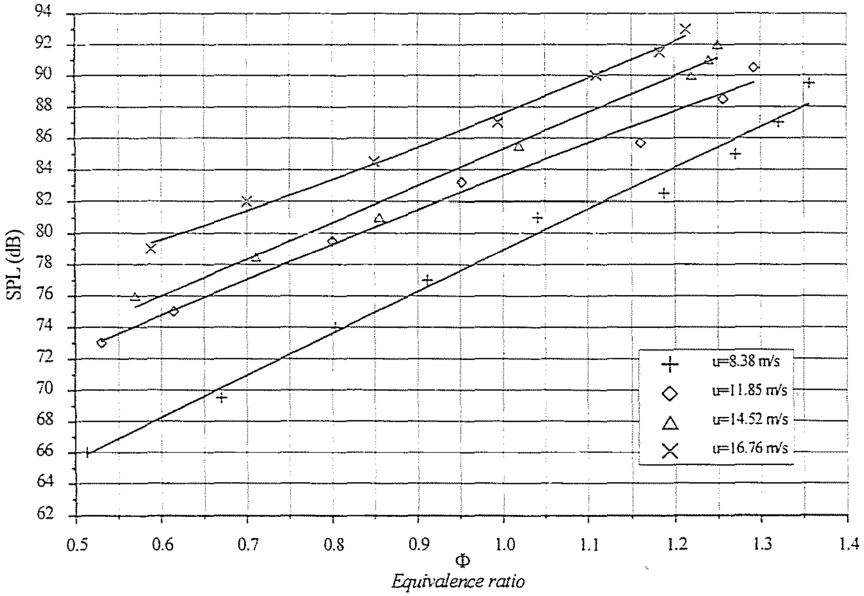

Fig. 12. Sound pressure level versus the equivalence ratio at different flow velocity, (fuel: natural gas, flameholder: cone, $BR = 0.42$, $h/d = 0$)

Nomenclature

BR = blockage ratio
C = velocity of the sound
D = distance from the microphone
d = burner diameter
E = volumetric expansion ratio
EQR, Φ = equivalence ratio
f = frequency
HWA = hot wire anemometer
h/d = dimensionless group for flameholder position
L/d = microphone position
ΔP = pressure fluctuation
r = flame front radius
S_u = burning velocity
SPL = average sound pressure level
Tu = turbulence intensity
u = average mainstream air velocity
$\dot{V}$ = fuel volume flow rate
β = inclination angle
η = thermoacoustic efficiency
ρ = density of the medium

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